FIRST QUARTERLY PERIODIC PROGRESS REPORT
FOR
DEVELOPMENT OF SOLAR-PANEL SYSTEM FOR THERMALLY ANNEALING RADIATION DAMAGED SOLAR CELLS

(1 JULY 1967 — 1 OCTOBER 1967)

CONTRACT NO. NAS5-10445

PREPARED BY
THE BOEING COMPANY
SPACE DIVISION
SEATTLE, WASHINGTON

FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

First Quarterly Periodic Progress Report

for

DEVELOPMENT OF SOLAR PANEL SYSTEM FOR THERMALLY

ANNEALING RADIATION DAMAGED SOLAR CELLS

(1 July 1967 - 1 October 1967)

Contract No.: NAS5-10445

Goddard Space Flight Center

Contracting Officer: S. Provenzano
Technical Monitor: Dr. P. H. Fang

Prepared by:

The Boeing Company

Space Division

Seattle, Washington

Technical Leader: D. R. Clarke

Project Manager: Henry Oman

for

National Aeronautics and Space Administration

Goddard Space Flight Center

Greenbelt, Maryland

ABSTRACT

The objective of Contract NAS5-10445 is to design and build two operable 1-square-foot solar cell panels capable of withstanding 10 thermal-annealing cycles from 20 to 450°C. The panels require a heating system and a means of switching the solar cells from their operating state to the annealing state, and vice versa.

The work accomplished during this first quarter included: (1) development of a thermal-diffusion bonding process for attaching silver interconnectors to solderless, silicon solar cells, (2) evaluation of 400-Hz motor operations in vacuum, (3) a thermal analysis to evaluate possible heating methods, and (4) a preliminary panel design.

Thermal-diffusion bonding was used to join silver interconnectors to solar cells without degrading the performance of the solar cells. The bonds withstood at least 500 grams in shear loading before failure. Photomicrographs of bonds show a diffusion of the silver interconnector into the silver contact of the solar cell. This bond will withstand over 500°C and it may be useful in other solar-cell applications.

Two 400-Hz motors have been tested in vacuum. They can be used to operate the panel heating system in a demonstration panel.

The thermal analysis included investigation of greenhouse heating, electrical heating, and a combination of the two for achieving a 450°C panel temperature. The greenhouse heating study is not complete because of lack of data on the emittance of H-film beyond 2.7 microns. The electrical heating analysis shows that a 10-layer aluminum-foil radiation shield may be required, but this analysis is incomplete about the amount of current that can be conducted through solar cells at 450°C without degrading cells.

The preliminary panel design uses lightweight space-qualified materials that are able to withstand 450°C. It consists of woven fiberglass stretched in a Kovar frame. Ceramic adhesives bond the solar cells to the the fiberglass substrate.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

As solar cells become damaged from space radiation their power output
decreases. Today, oversized solar-cell panels are designed to provide
adequate output power at the end of the mission. However, with the new
large solar panels, such as the 5000-square-foot LASA (Reference 1), the
added weight and cost of an oversized panel are great enough to justify
a search for alternate methods of dealing with radiation degradation.
The NASA-Goddard Space Flight Center has shown that solar cells that have
become damaged from particulate radiation can be restored to their initial
state by thermal annealing (Reference 2). The temperature required for
thermal annealing is a function of radiation energy, flux, and annealing
time. To date, only individual solar cells have been annealed thermally.

An objective of Contract NAS5-10445 is to develop two 1-square-foot solar
panels with interconnected, operable solar cells capable of withstanding
10 temperature cycles from 20 to 450°C. In addition, the panels must
have an auxiliary system that will: (1) produce the heat required to
elevate the panel to 450°C within 1 hour, and (2) switch the solar cells
from the operating state to the annealing state, and vice versa.

At the time this work was started the most difficult problems were anti-
cipated to be:
1) Developing a practical method of interconnecting solar cells so that
   the assembly can withstand heating to 450°C;
2) Developing a practical solar or electrical method of heating the
   panel to 450°C.

This report describes results achieved during the first 3 months of a
12-month program.

TECHNICAL DISCUSSION

This section describes the work accomplished during the first quarter of
the 12-month contract in the following order:

1)   Thermal-diffusion bonding;

2)   Shade motor evaluation;

3)   Thermal analysis;

4)   Panel design.

THERMAL-DIFFUSION BONDING

The contract work statement requires that the solar-cell panel be capable
of withstanding 10 cycles of temperature change from 20 to 450°C. The
critical element is the solar-cell interconnector joint, which today is
commonly made using conventional "soft" solder having a melting point of
190°C. Brazed interconnectors do not appear practical because brazing
temperatures, which are above 550°C, create permanent damage in the solar
cell. Mechanical fasteners could withstand 450°C, but they occupy panel
area and introduce doubts with respect to contact resistance following
temperature cycling.

A method was sought to join the interconnector to the solar cell at a
temperature below 500°C without the joint failing at 450°C. The method
that appeared most suitable for this type of joining was thermal-diffu-
sion bonding. The metals to be joined are placed in intimate contact
under pressure and heated to half their melting points, at which time
the metals diffuse together (Reference 3). After diffusion, the joint
will not separate under moderate stress until it is heated to the melt-
ing point of the metal.

This technique has now been used to make the joint between the inter-
connector and the solar cell (Figure 1). It produced an excellent bond
without degrading the solar cell. The joints have been found to be
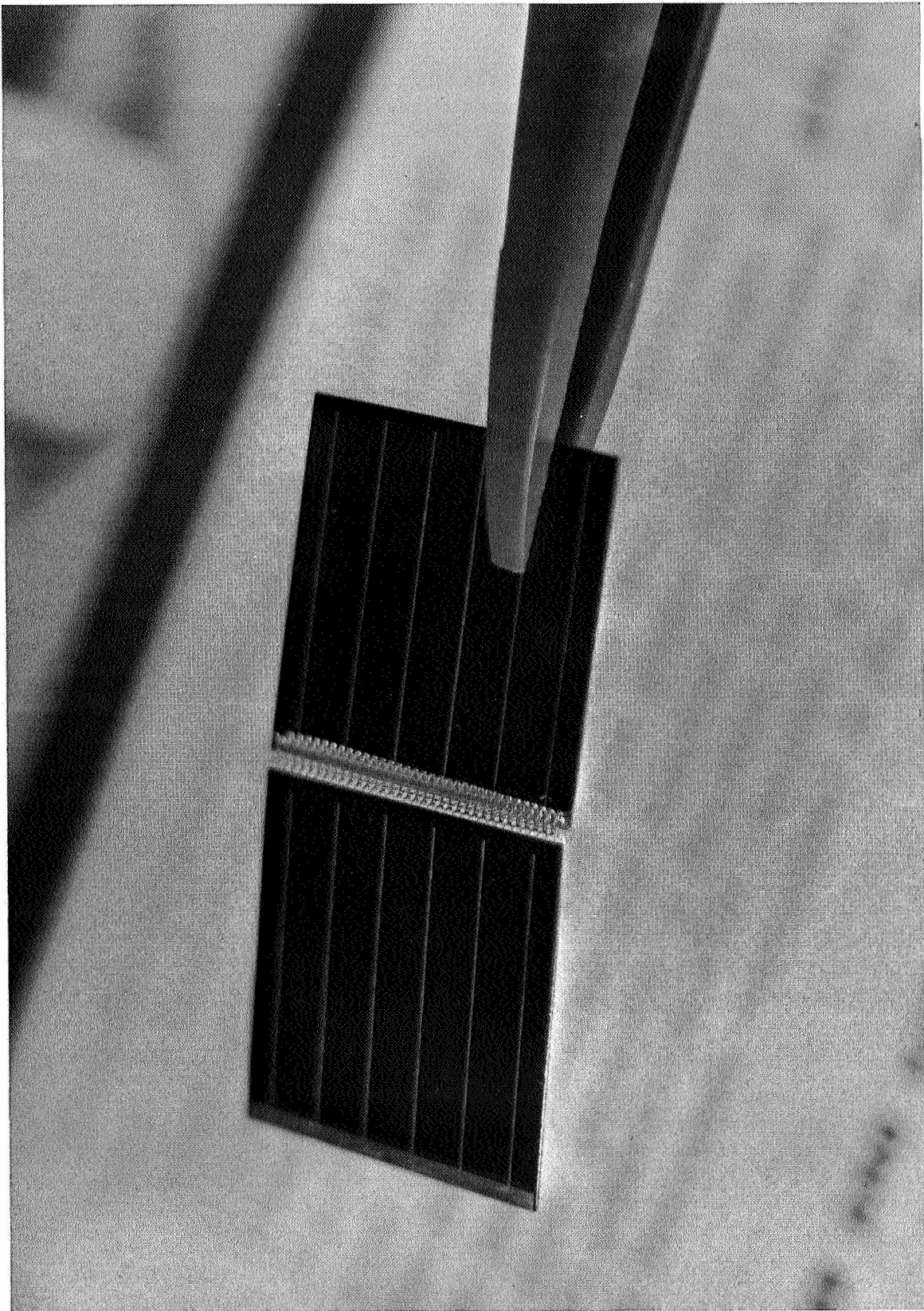capable of withstanding repeated temperature cycles from 20 to 500°C.

2

Figure 1:   SOLAR CELLS IN SERIES WITH THERMALLY
DIFFUSED SILVER INTERCONNECTOR

3

The thermal-diffusion bonding tool built at Boeing for making the solar-cell interconnector joint is shown in Figure 2. This tool is made from mild steel. It is based on two other tools that were used to show the feasibility of using thermal-diffusion bonding on solar cells. This new tool is being used to join interconnectors to 50 solar cells that will be tested electrically and mechanically.

The solar cells and silver-mesh interconnector are located on the tool base as shown in Figure 3. The tool top is then placed on the assembly as shown in Figure 4. Pressure is applied to the joint with the wedge-shaped piston that is inserted into the sleeve (Figure 5). Copper rods are placed inside the piston to act as expansion members and the steel bar is placed over the rods. Nuts are screwed onto the studs and pressure is applied to the wedge. The nuts are tightened fingertight, plus one-eighth turn.

The tool, with solar cells and interconnector, is then placed in a vacuum chamber, which is evacuated to 1×10^{-4} torr. The tool is then heated to 400°C, at which temperature it is soaked for 20 minutes and then cooled. After cooling, the solar cell and interconnector are removed from the tool, and the joint is inspected under a microscope.

The required thermal-diffusion bonding pressure is 5600 pounds per square inch at the joint, but there is not yet an accurate way of measuring the pressure or of knowing what happens to the pressure during heating. Inspection of the satisfactorily completed joint suggests that the correct pressure is being applied to the joint. A precise way is being sought to measure the pressure at the joint and to calibrate this in terms of an acceptable bond. For example, hastalloy or inconel springs will be substituted for the copper rods in order to control the force applied to the top of the piston.

The temperature used for bonding is measured with a thermocouple attached to the tool. Prior work in joining silver to silver showed that the thermal-diffusion process is relatively insensitive to temperatures from 250 to 400°C. However, the theory of diffusion favors high temperature
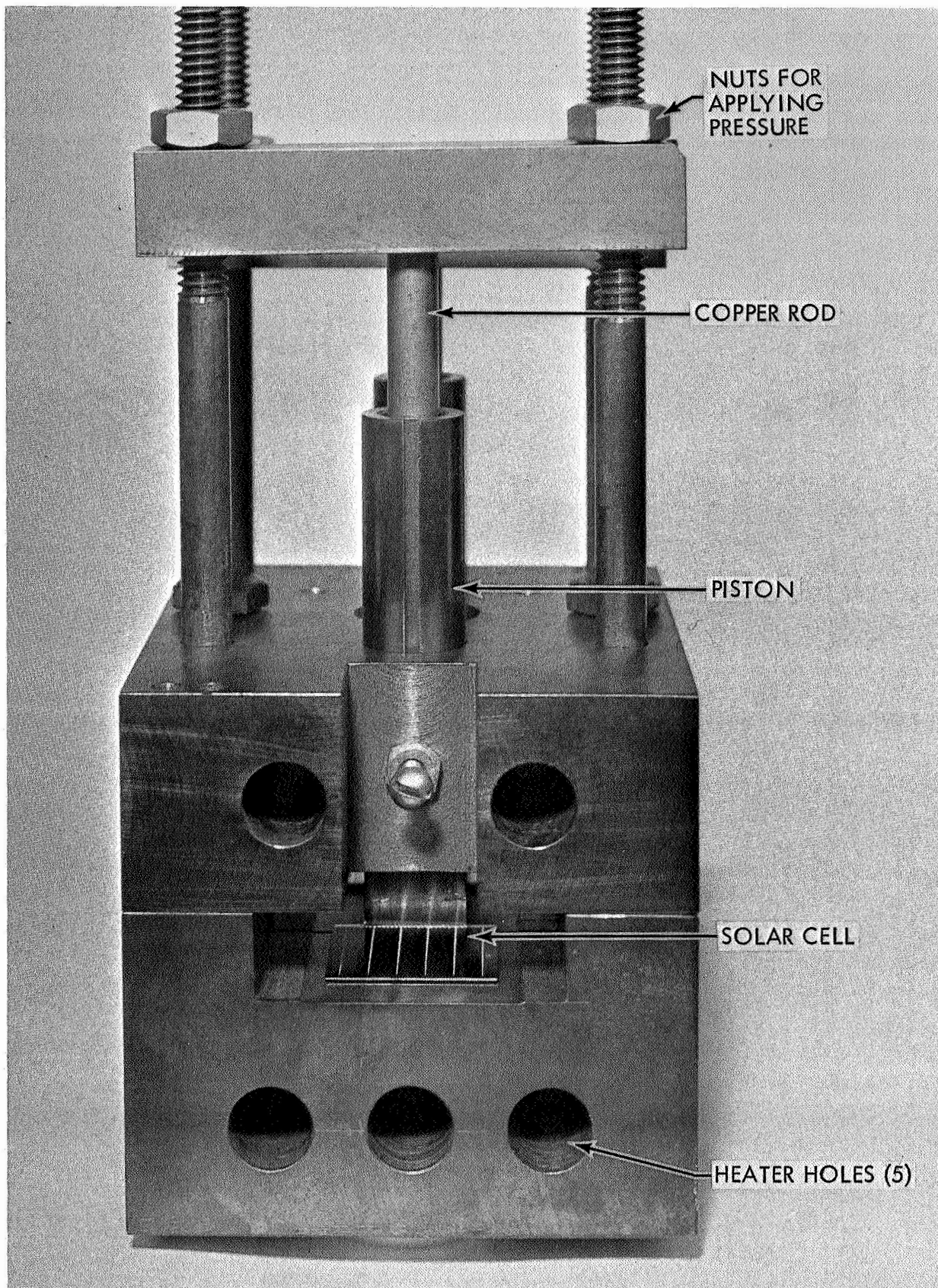
Figure 2: TOOL FOR THERMAL DIFFUSION BONDING TO SOLAR CELLS

5

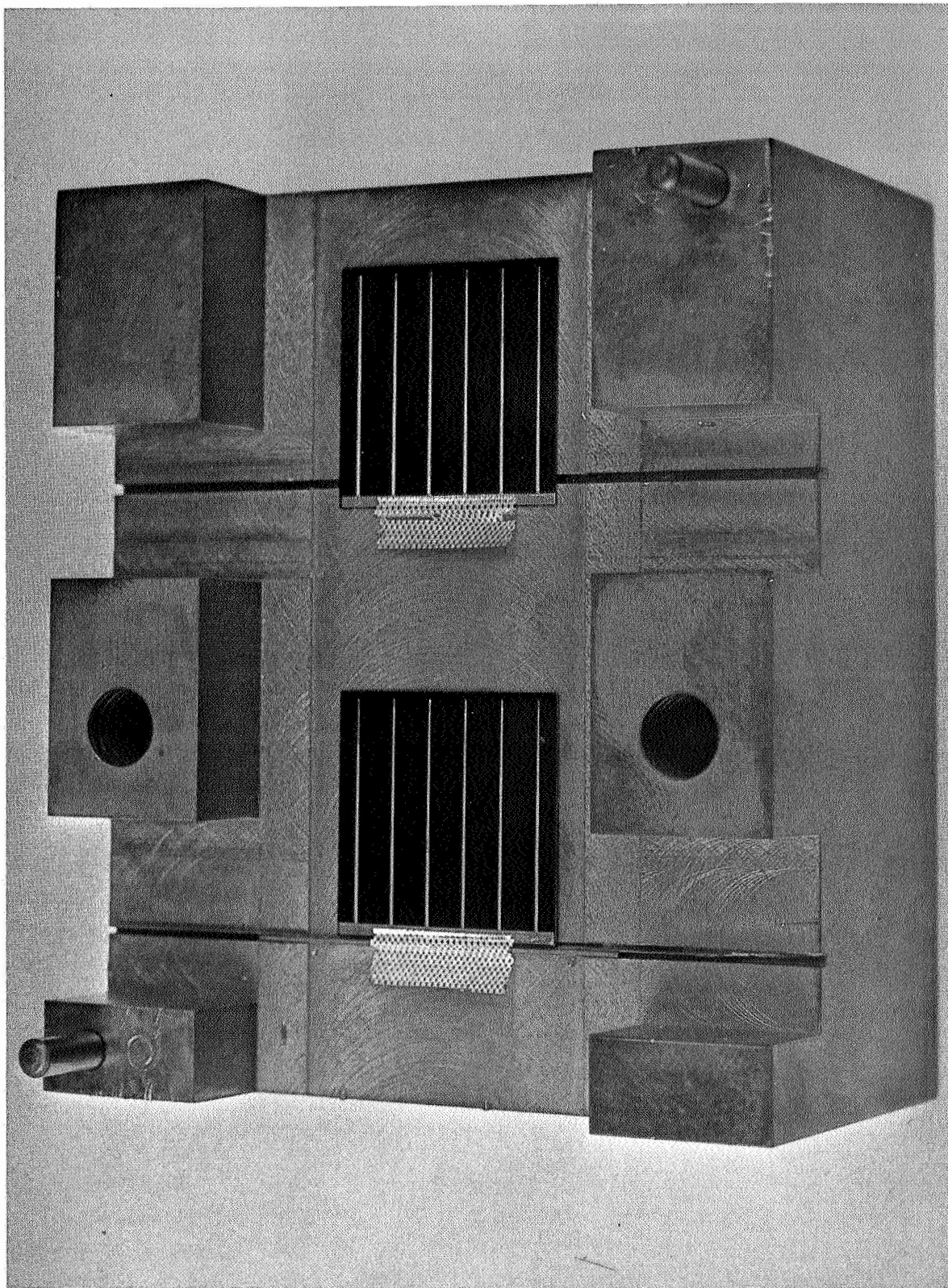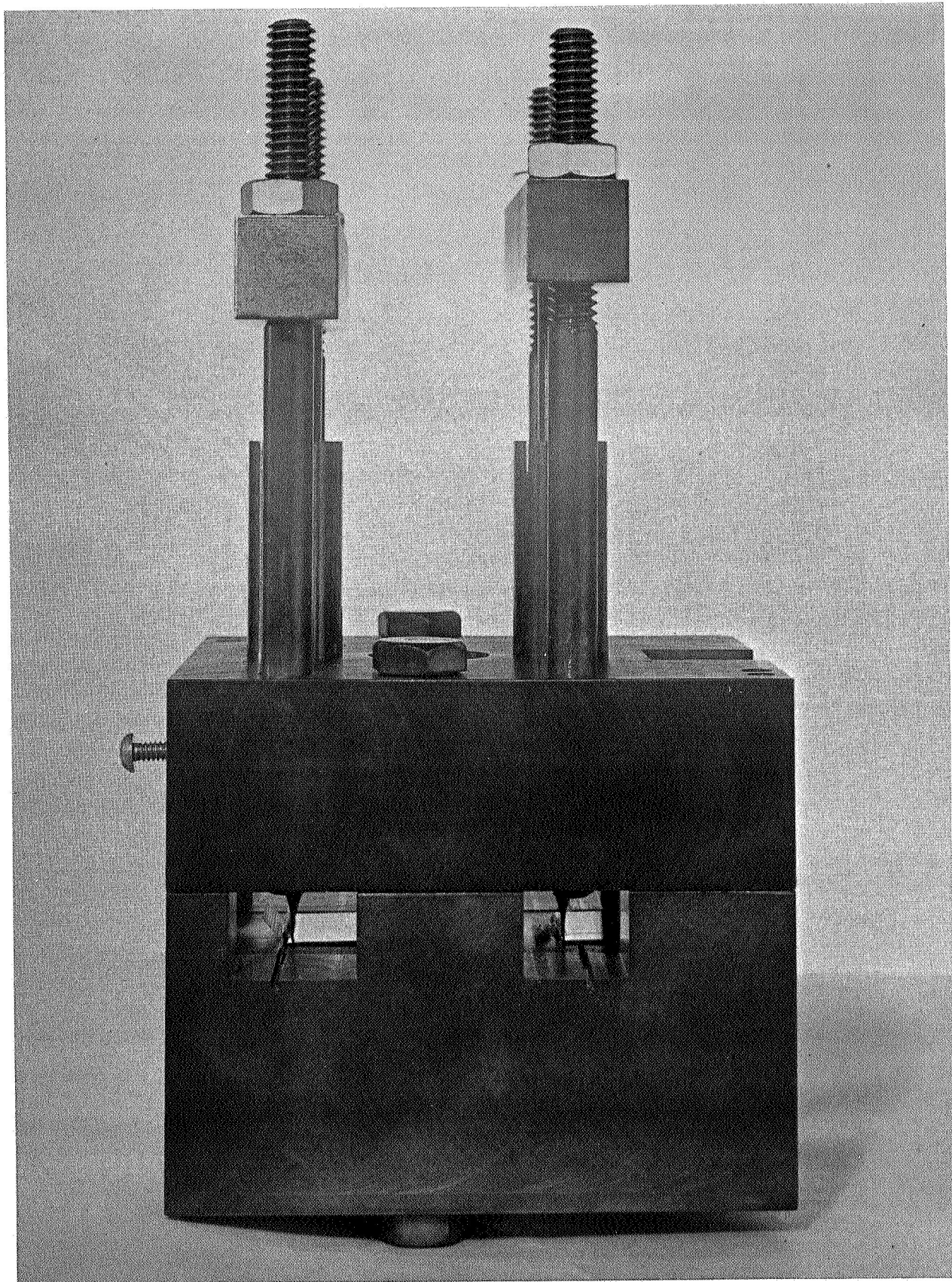Figure 3: SOLAR CELL IN BONDING TOOL

6

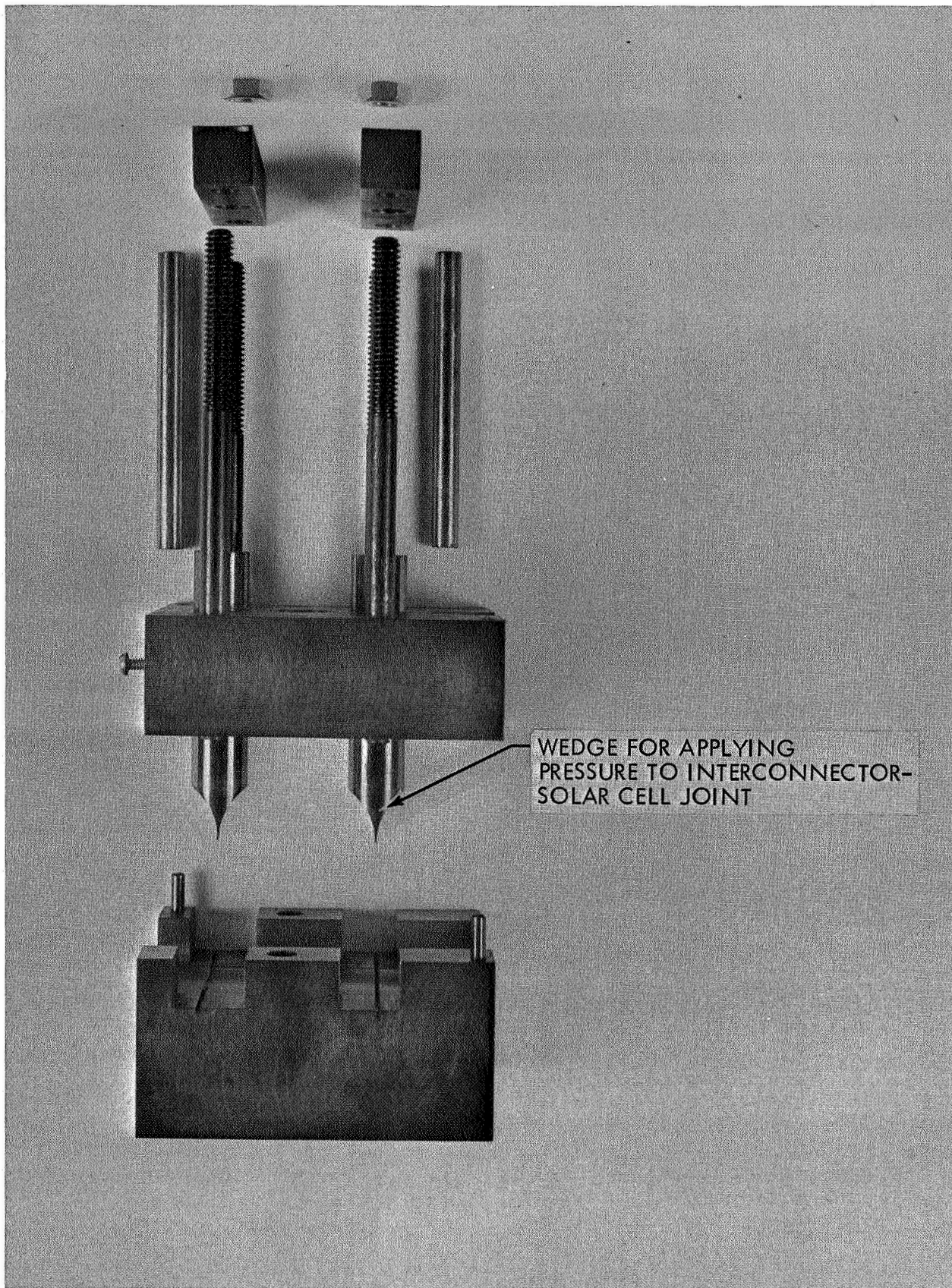Figure 4:   PISTON APPLYING PRESSURE TO SOLAR CELL INTERCONNECTOR JOINT

WEDGE FOR APPLYING PRESSURE TO INTERCONNECTOR-SOLAR CELL JOINT

Figure 5:   EXPLODED VIEW OF THERMAL DIFFUSION BONDING TOOL

CONTRACT NO. NAS5-10445

which also shortens diffusion time. It was decided to use the 400°C temperature, which was attained by placing five 400-watt heaters in the tool and controlling the power with a Variac.

In the initial work, the time at bonding temperature did not appear to be too critical. Silver was bonded to silver through a range of 1 to 10 minutes with good bonds resulting. Bonding times of less than 1 minute were not investigated because at this time there appeared to be no advantage to shorter times. With the tools being used, the heating and cooling cycle takes about 100 minutes.

However, after several bonds were made between the interconnector and solar cell with a bonding time of 5 minutes, it was seen that the bond was not continuous and would lift up at the ends. The time was increased in 5-minute steps, and at 20 minutes it was found that good continuous bonds could be made repeatedly. A 20-minute soak time is currently being used for forming the interconnector/solar-cell joint.

Reference 3 states that thermal-compression bonding must be done in either a vacuum or in an inert atmosphere. Because of the availability of vacuum chambers in the Boeing solar power laboratory, it was decided to do the bonding in vacuum. An advantage of using vacuum is that parts being bonded become clean as they are heated. The highest air pressure that can be used during bonding has not yet been determined. A pressure of 1×10^{-4} torr was arbitrarily selected because this is a pressure that can be easily attained within a few minutes after roughing the vacuum chamber.

The vacuum system being used for this work consists of a 14-inch-diameter bell jar that is pumped with a Consolidated Vacuum Corporation (CVC) 4-inch diffusion pump and rough-pumped with a Heraus Model DK 20 pump. This vacuum system will be used for the thermal-diffusion bonding during the interconnector development. The maximum pressure that can be used during bonding will be determined because a vacuum chamber may not be available for bonding the quantity of solar cells that will be needed to make the 1-square-foot, solar-cell panel.

PERFORMANCE CURVES ON SOLAR CELLS

The cell/interconnector assemblies used in performance tests reported
herein were made with one of the early thermal-diffusion bonding tools.
This tool produced good joints, but the cell breakage was about 50%.
The new tool previously described has solved this breakage problem.

The performance of solar cells was measured before thermal-diffusion
bonding, and again after bonding. It was felt that more than 5% decrease
in cell maximum power would be unacceptable. A group of 15 low-efficiency,
2- by 2-cm solar cells was selected for this first study. The cells were
washed in ethanol, and performance curves were drawn. Of the 15 solar
cells, only seven showed a "knee" in the current-voltage (IV) curve.
All curves showed a low short-circuit current for the solar-cell size and
the test conditions, which were a 28°C solar-cell temperature and a light
intensity of 100 mw/sq cm from an unfiltered xenon lamp.

Interconnectors were then bonded to the "n" contact of the solar cell and
the performance was again measured. Of the seven good cells, only four
were bonded to interconnectors without the cell breaking. The performance
of these four solar cells was measured again, and the change in the maxi-
mum power is shown in Table I.

Table I: SOLAR-CELL PERFORMANCE AFTER THERMAL-DIFFUSION BONDING

Cell No.	Maximum-Power Change Resulting From Bonding (%)
7	+ 4.9
8	+ 3.9
9	− 5.9
18	+ 4.2

An IV curve, showing the performance increase measured after bonding, is
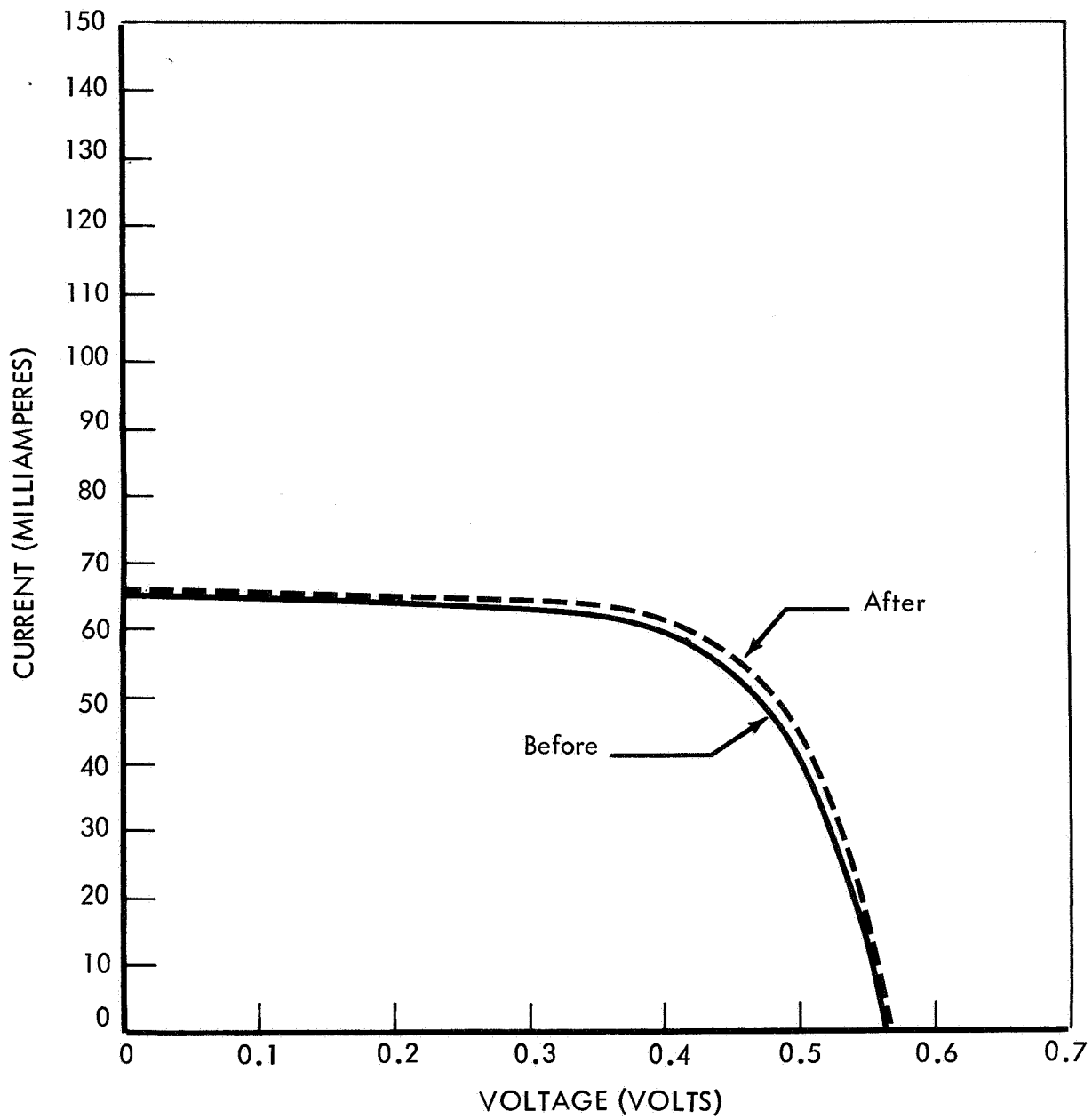shown in Figure 6.

10

Figure 6: SOLAR CELL PERFORMANCE BEFORE AND
AFTER THERMAL-DIFFUSION BONDING

11

The reproducibility of solar-cell performance curves with the laboratory setup is ±2%. The data in Table I shows that three of the four solar cells developed increased output after diffusion bonding. A possible explanation appears in Reference 2 where it is shown that solar cells increase in output after heating. However, it must also be noted that the cells tested were not high-quality cells, and the effect of heating on their originally poor performance is obscure.

The decrease in performance of solar-cell No. 9 cannot be explained at this time. The bond appeared good and no cracks could be seen in the solar cell. One other solar cell that showed a decrease in performance after thermal-diffusion bonding was examined under a microscope. A chip at one corner at the "n" contact could be observed. This chip appeared to be the cause for degradation in the solar cell.

These data show that a solar cell can be joined to an interconnector using thermal-diffusion bonding. However, to show conclusively that this is a good process, 20 good cells will be bonded with the new tool. Test results will be analyzed statistically. The resulting data will appear in the next quarterly report.

SOLAR TESTS ON CELL-INTERCONNECTOR JOINT

The eight solar cells that showed poor performance prior to bonding were selected for the shear tests. Interconnectors were bonded to the solar cells and again the attrition through breakage was appalling. However, enough pieces were salvaged to make shear tests on the interconnector to solar-cell joint. A clamp was made to grasp the interconnector, and the solar cell was held firmly between the fingers. The clamp was loaded with weights until the joint failed. The results of this test are shown in Table II.

Table II: RESULTS OF SHEAR TESTS ON THERMAL-DIFFUSION-BONDED
INTERCONNECTOR TO SOLAR-CELL JOINTS

Cell No.	Load (Grams)
10	500
11	1250
15	750
16	500

This test is not conclusive, but was done only to establish confidence in the mechanical strength of the bonded joint. In all tests either the failure occurred in the silver mesh or the contact pulled away from the cell. In no case did the bonded joint separate. From this initial data it appears that a joint formed by thermal-diffusion bonding is stronger than the silver mesh, and stronger than the contact-to-silicon joint.

With the new bonding tool, 20 cells will be joined and tested using the Unit Micropull Pull-Strength Tester. The results will be analyzed statistically, and the data will be presented in the next quarterly report.

MICROSCOPE EVALUATION OF INTERCONNECTOR JOINT

Four of the solar cells were cross-sectioned perpendicular to the "n" contact, polished, and photographed with an electron microscope. A picture of the cross section of one of the solar cell/interconnector joints (which is typical of the others) is shown in Figure 7. The fine black line above the "n" contact is the boundary between the contact and the interconnector. A close examination of this line shows where the grains of metal have coalesced across the boundary. This grain growth across the boundary shows that the interconnector and contact are forming into one part, which is the best type of bond one can expect.
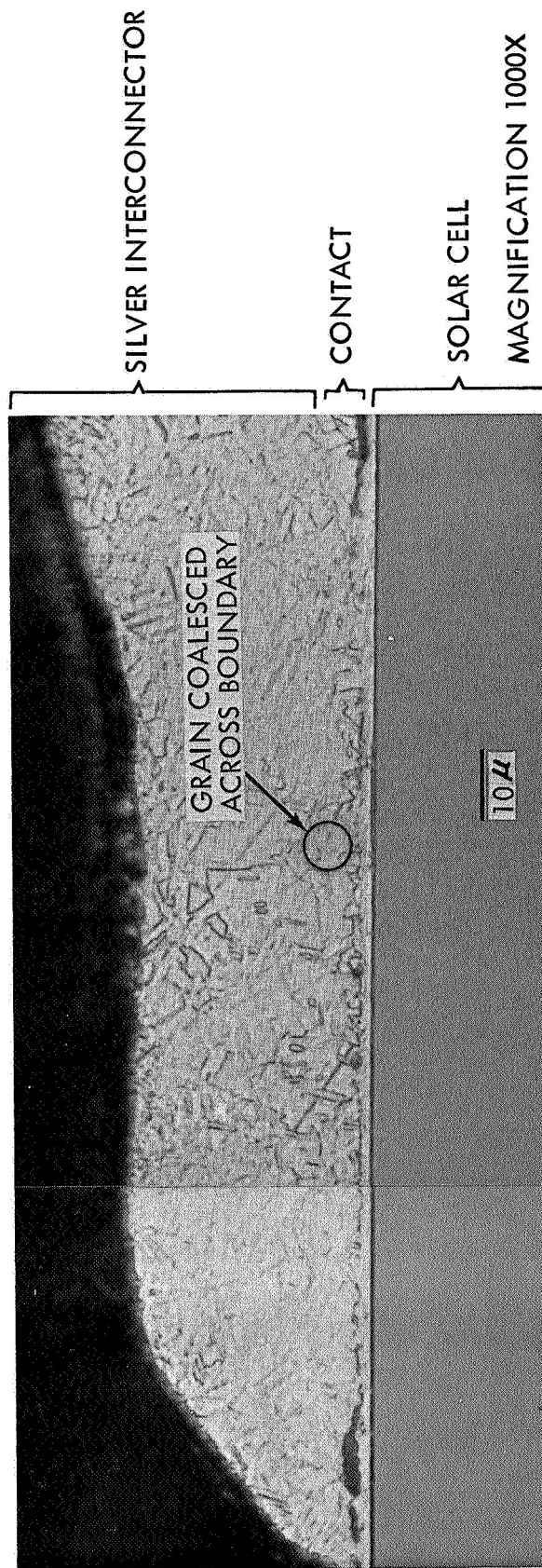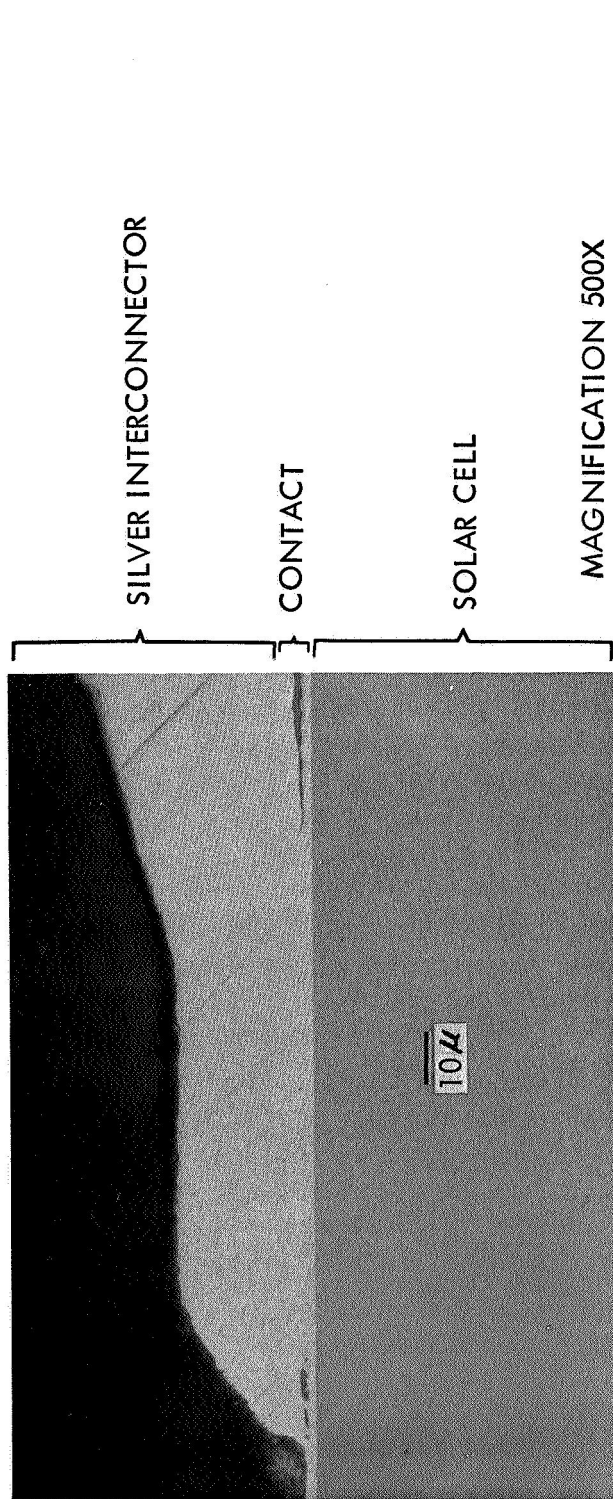
13

SILVER INTERCONNECTOR

CONTACT

SOLAR CELL

MAGNIFICATION 500X

SILVER INTERCONNECTOR

CONTACT

SOLAR CELL

MAGNIFICATION 1000X

GRAIN COALESCED ACROSS BOUNDARY

10 μ

10 μ

Figure 7: PHOTOMICROGRAPHS OF INTERCONNECTOR TO SOLAR CELL JOINT

14

THERMAL CYCLING OF SOLAR CELL AND INTERCONNECTOR

The contract requires that the solar-cell panel be capable of withstanding 10 temperature cycles from 20 to 450°C. In view of this requirement, three solar cells with bonded interconnectors were cycled 10 times from 20 to 500 °C. This test shows that the interconnector will not separate from the solar cell after repeated cycles.

During the next reporting period the thermal cycling test will be repeated and performance curves of the solar cell will be obtained before and after the test to determine degradation if any from thermal cycling.

The work done during this quarterly reporting period indicated that thermal-diffusion bonding can be used with solar cells, the process will not degrade the solar cell, and the bond will not fail after repeated temperature cycles to 450°C. This work is primarily exploratory, and the incompleteness of the tests and the inadequacy of sample size should be recognized.

With the new bonding tool, cells will be systematically measured, bonded, and tested. The test data will be analyzed statistically and it will show (hopefully) that thermal-diffusion bonding will satisfactorily meet and exceed the requirements of the work statement.

SHADE MOTOR EVALUATION

An electric motor is required for drawing a shade over the panel during the thermal annealing and for retracting the shade after annealing. For space flight a space-qualified, brushless, d.c. electric motor would be required. These motors cost from $2,500 to $50,000 each, a prohibitive sum for the demonstration panels to be built on this contract. Boeing proposes to use 400-Hz a.c. motors on the panels for this contract, but will show on supplementary drawings the brackets and accessories required for the space-qualified motors.

TESTS ON 400-Hz MOTORS

Two 400-Hz motors were procured and operated in vacuum at a pressure of
25 microns for 1 hour. At the end of the test the motors were stopped
and restarted to determine if the bearings would seize. No seizure was
noted.

One motor, made by Induction Motors Corp., is geared to run at 50 rpm.
The other motor, made by Globe Industries, Inc., is geared to run at 4.0
rpm. The lower-speed motor appears to be better suited for this particu-
lar application.

Space-qualified bearings can be obtained from The Barden Corporation in
the event that bearing seizure becomes a problem. Also, all gears and
moving parts can be coated with molybdenum-disulfide using a Boeing
process (BAC 58-11). This process was used on parts flown on the Lunar
Orbiter spacecraft.

THERMAL ANALYSIS

To have cool solar cells that are efficient in space, the front surface
of the solar cells and the back surface of the panel must have a high
thermal emittance. However, the high emittance of the panel surfaces is
not compatible with heating the panel to 450°C. To heat a 1-square-foot
panel to 450°C in space without a shroud would require 2700 watts.

To reduce the power required for heating, a retractable cover will be
drawn over the front and back of the panel during annealing. It has been
suggested by NASA-Goddard Space Flight Center that the covering on the
front of the panel be made from materials such as H-film that would pro-
mote "greenhouse" heating. The three methods Boeing is investigating
for heating the panel in space are: (1) greenhouse heating with H-film
and coated H-film, (2) electrical heating by passing current in the
forward direction through the solar cells, and (3) heating by a combina-
tion of (1) and (2).

16

Work has been done in analyzing methods (1) and (2). The characteristics of solar cells with 1 ampere of current at various temperatures have been investigated. These solar-cell characteristics are important in that they establish the power that can be released as heat by the solar cells while carrying current.
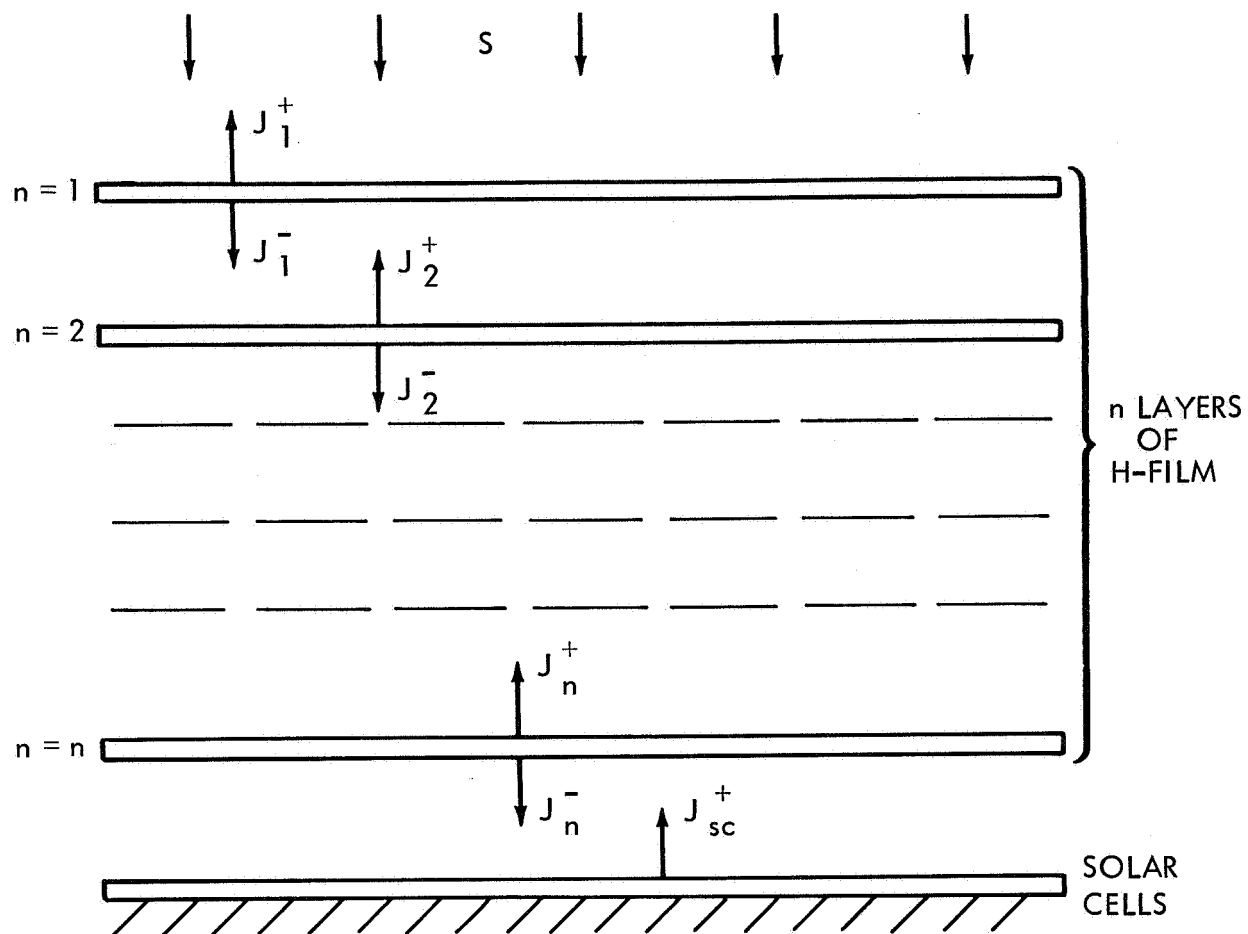
GREENHOUSE METHOD

The initial thermal analyses of the greenhouse method were based on the back side of the solar cell array being adiabatic (no heat losses). This assumption is justified on the basis that initial analyses are only feasibility studies of the method. The problem is then one of solar radiosity and infrared radiation on the Sun side of the solar-cell array.

A simple iterative BLITZ (simplified FORTRAN) program was written to solve the radiosity problem in the solar spectrum. This program uses the equations presented in Figure 8 to solve for the solar heat input, Q, to each of the n layers of H-film and the solar cells. The optical properties of the H-film and the solar cells are given as well as the solar flux, S. Solar reflectance is ρ, solar transmittance is τ, and radiosity is J.

Given the solar heat input, Q, to each of the n layers of H-film and the solar-cell array, radiation heat balance equations can be written for each layer and the solar-cell array using the following terms:

$$Q_1 + \sigma \mathcal{F}_F \ (T_2^4 - T_1^4) = \sigma \epsilon_F T_1^4$$

$$Q_2 + \sigma \mathcal{F}_F \ (T_3^4 - T_2^4) = \sigma \mathcal{F}_F \ (T_2^4 - T_1^4)$$

$$Q_n + \sigma \mathcal{F}_{CF} \ (T_{SC}^4 - T_n^4) = \sigma \mathcal{F}_F \ (T_n^4 - T_{n-1}^4)$$

$$Q_{SC} = \sigma \mathcal{F}_{CF} \ (T_{SC}^4 - T_n^4)$$

17

Figure 8:   RADIOSITY EQUATIONS

$$J_1^+ = \rho_1 S + \tau_1 J_2^+ \qquad\qquad J_1^- = \tau_1 S + \rho_1 J_2^+$$

$$J_2^+ = \rho_2 J_1^- + \tau_2 J_3^+ \qquad\qquad J_2^- = \tau_2 J_1^- + \rho_2 J_3^+$$

$$J_n^+ = \rho_n J_{n-1}^- + \tau_A J_{sc}^+ \qquad\qquad J_n^- = \tau_n J_{n-1}^- + \rho_n J_{sc}^+$$

$$J_{sc}^+ = \rho_{sc} J_n^- \qquad\qquad\qquad J_{sc}^- = O$$

$$Q_1 = S + J_2^+ - J_1^+ - J_1^-$$

$$Q_2 = J_1^- + J_3^+ - J_2^+ - J_2^-$$

$$Q_n = J_{n-1}^- + J_{sc}^+ - J_n^+ - J_n^-$$

$$Q_{sc} = J_n^- - J_{sc}^+$$

SOLAR
HEAT
INPUT

18

where:

σ = Stephan-Boltzmann constant

$$\mathcal{J}_F = \frac{\epsilon_F}{2 - \epsilon_F}$$

ϵ_F = infrared emittance of the H-film ($\epsilon + \rho_{IR} = 1$)

$$\mathcal{J}_{CF} = \frac{1}{1/\epsilon_F + 1/\epsilon_{CF} - 1}$$

ϵ_{CF} = infrared emittance of the solar cells.

These terms can be rearranged and manipulated to give the following equation for the steady-state temperature of the solar-cell array:

$$T_{sc} = \left\{ \frac{Q_{sc}}{\sigma \mathcal{J}_{CF}} + \frac{1}{\sigma \mathcal{J}_F} \left[(n)(Q_{sc}) + Q_{TOT} \left(\frac{\mathcal{J}_F}{\epsilon_F} - 1 \right) + \sum_{i=1}^{n} i Q_i \right] \right\}^{1/4}$$

where $Q_{TOT} = Q_{sc} + \sum_{i=1}^{n} Q_i$

Initial calculations of the steady-state solar-cell temperatures with assumptions as shown are presented below, assuming a near-Earth solar constant (442 Btu/hr ft^2):

Case No.	n	$(\alpha_s)_{sc}$	$(\zeta_s)_F$	$(\rho_s)_F$	$(\alpha_s)_F$	ϵ_{sc}	ϵ_F	$T_{sc}(°C)$
1	6	0.7	0.841	0.083	0.076	0.85	0.60	372
2	8	0.7	0.841	0.083	0.076	0.85	0.60	396
3	10	0.7	0.841	0.083	0.076	0.85	0.60	412
4	10	0.7	0.349	0.301	0.35	0.85	0.60	201

Cases 1 through 3 were performed initially for optical solar properties thought to be indicative of uncoated H-film (Reference 4). Further analyses of uncoated H-film led to the following properties (solar):

α_s = 0.276

τ_s = 0.635

ρ_s = 0.089

In addition, it appears from the limited data available (to 2.7 microns) that uncoated H-film may be highly transparent in the infrared, thus rendering the above analysis incorrect and the feasibility zero. Additional spectral data on H-film are being obtained.

Case 4 is representative of coated H-film (Reference 4). Here, the H-film indeed appears opaque in the infrared and also appears to exhibit a low emittance. Again, however, additional spectral data is required before a firm conclusion can be reached. What is desired is a film opaque in the infrared with a low emittance and yet having high transparency in the solar spectrum.

ELECTRICAL HEATING

A thermal mathematical model of an electrically heated panel has been programmed on the Boeing Engineering Thermal Analyzer (BETA-II). The initial model assumed the use of 10 layers of 1-mil aluminum foil on each side of the panel, placed at a layer density of 20 layers per inch. Layer density affects edge heat losses. The aluminum is assumed to be opaque with an infrared emittance of 0.03. Infrared emittance of each side of the panel is assumed to be 0.85, and the infrared emittance of the exposed edges of the panel is assumed to be 0.10.

With these conditions, Figure 9 presents the steady-state equilibrium temperature of the solar cells as a function of the heat input. It shows that the solar cells at 450°C must dissipate 45 watts per square foot of power at steady-state conditions. However, 45 watts is not enough power to heat the solar cells to 450°C in less than 1 hour.

It will be shown later that solar-cell characteristics are such that more than 45 watts per square foot might be released at lower temperatures to bring the panel temperature to 450°C in less than 1 hour. This assumes that the solar cells can withstand the current necessary for this power without degrading.
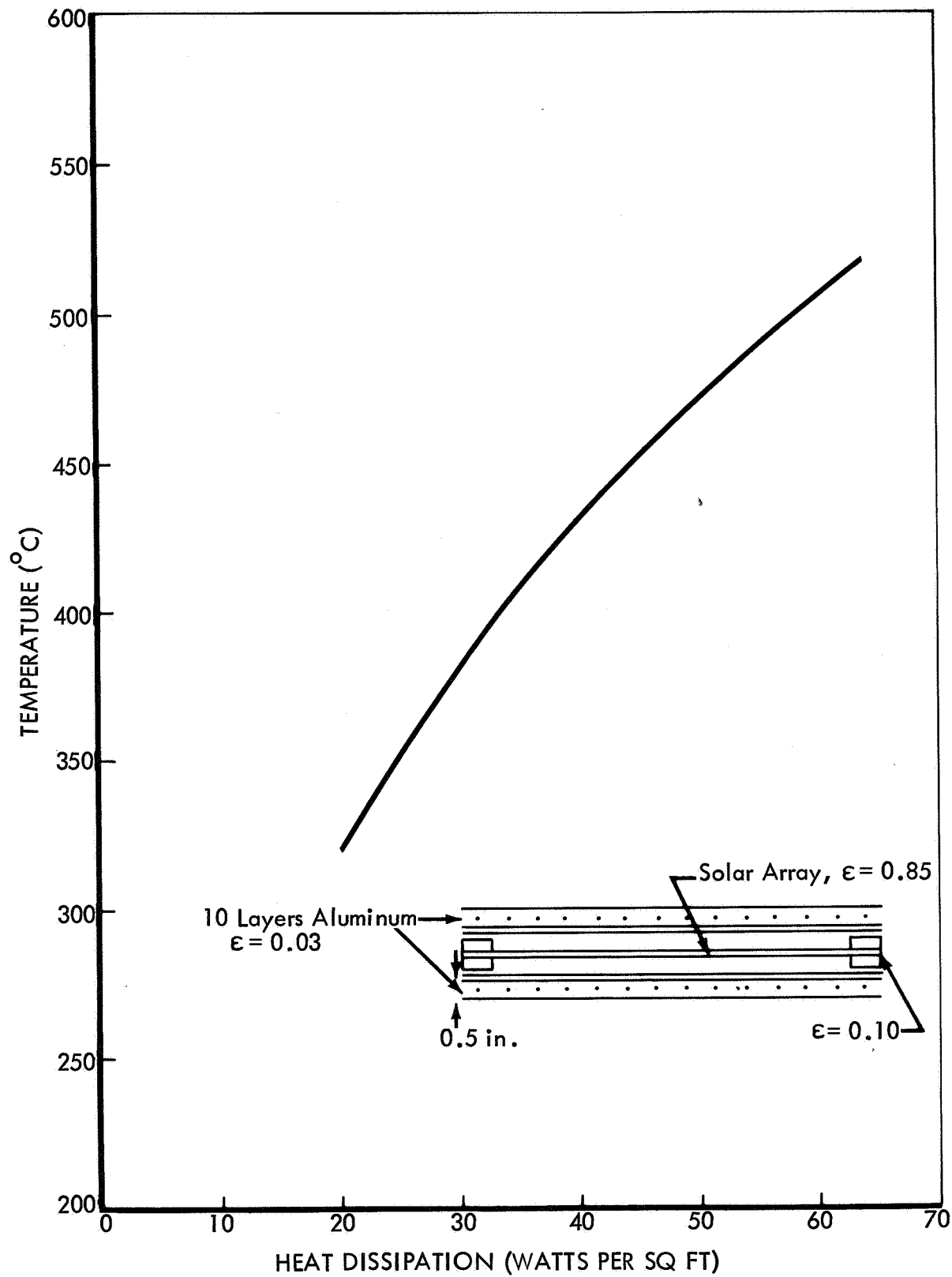
Figure 9:   STEADY-STATE SOLAR-CELL TEMPERATURE

CONTRACT NO. NAS5-10445

The steady-state temperature of 450°C will require 0.77 ampere in the forward direction through the solar cells. Further trades with respect to the number of layers of insulation versus the power requirements will be made when it is learned how much current a solar cell can withstand at 450°C without degrading.

SOLAR-CELL CHARACTERISTICS DURING HEATING

In the event that Method 2 or 3 is used to heat the solar panel, it is necessary to know the characteristics of solar cells at high temperatures. A 1- by 2-cm solar cell was placed in a dark chamber and leads were connected on the "n" and "p" contacts mechanically. The forward current of the cell was measured as a function of voltage at temperatures from 40 to 500°C. The resulting curves appear in Figure 10. This curve shows that with constant current, and at the low temperatures, a greater amount of power can be released as heat than at the higher temperatures. It also shows that constant-voltage heating without a current limit creates a runaway condition.

With 10 layers of aluminum-foil shading, 45 watts per square foot of power is required at 450°C. This corresponds to 0.77 ampere through the solar cell. The performance of the solar cells after being heated to 450°C with 0.77 ampere of current has not yet been measured. The performance of solar cells before and after heating to 450°C will be measured to determine degradation due to high current. A trade will then be made as to the amount of shade insulation versus the power requirements to heat the panel and maintain a steady-state temperature.

PANEL DESIGN

The panel design is comprised of two parts. The first part is the design of a structure that is lightweight, capable of supporting solar cells, and capable of 10 repeated temperature cycles from room temperature to 450°C in vacuum. The second part is the design of a shade with the supporting reels and necessary gear trains and pulleys for extending and
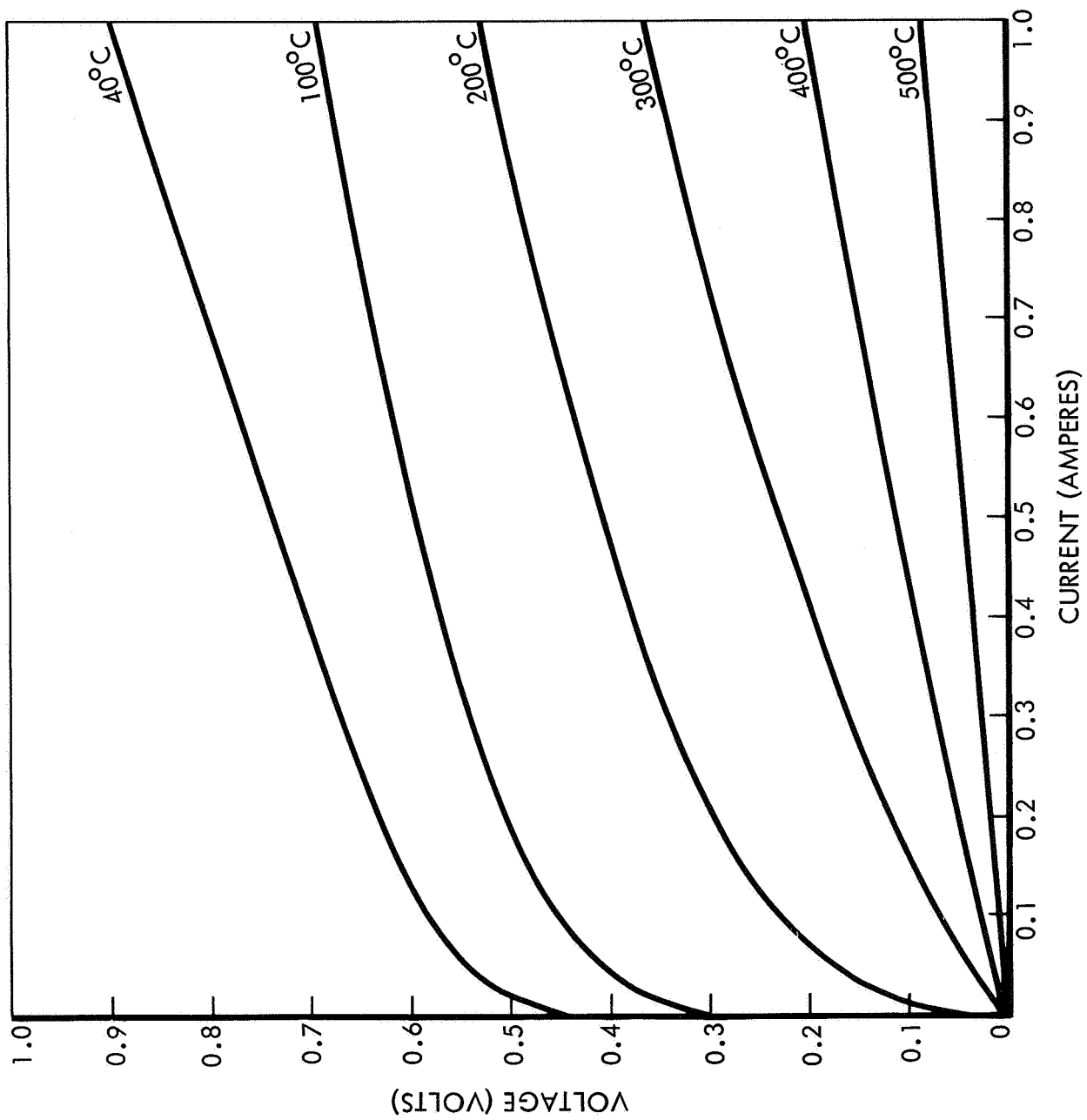
22

Figure 10: CHARACTERISTICS OF A 1-BY 2-CM SILICON SOLAR CELL AT VARIOUS TEMPERATURES

23

retracting the shade in vacuum at 450°C. The shade and supporting structure cannot be discussed at this time because its design depends on the results of the thermal analysis.

SUBSTRATE DESIGN

A preliminary panel design is shown in Figure 11. The panel substrate is 5-mil woven fiberglass cloth that is supported around the edge with a Kovar-channel frame. Solar cells are cemented to the substrate with ceramic cement. Cement will be placed between the Kovar channels to prevent the fiberglass from unraveling if this becomes a problem. All materials are based on their ability to retain strength at elevated temperatures and on their coefficients of thermal expansion.

The fiberglass cloth has a thermal emittance of 0.80 on the back side with a solar cell cemented to the front side of the cloth. This high emittance eliminates the need for a thermal control coating on the back of the panel. The cements used to hold the solar cells will be kept as thin as possible, perhaps 3 to 5 mils, to obtain high thermal conductivity from the solar cell to the back of the panel to keep cell temperature low for efficient solar energy conversion. The Kovar channels will be riveted together, and stainless steel brackets will be placed on the ends for supporting the shade reels and motor.

A trial panel with cull solar cells will be built and tested before the final panel design is adopted. This will be done during the third quarter of this contract period.
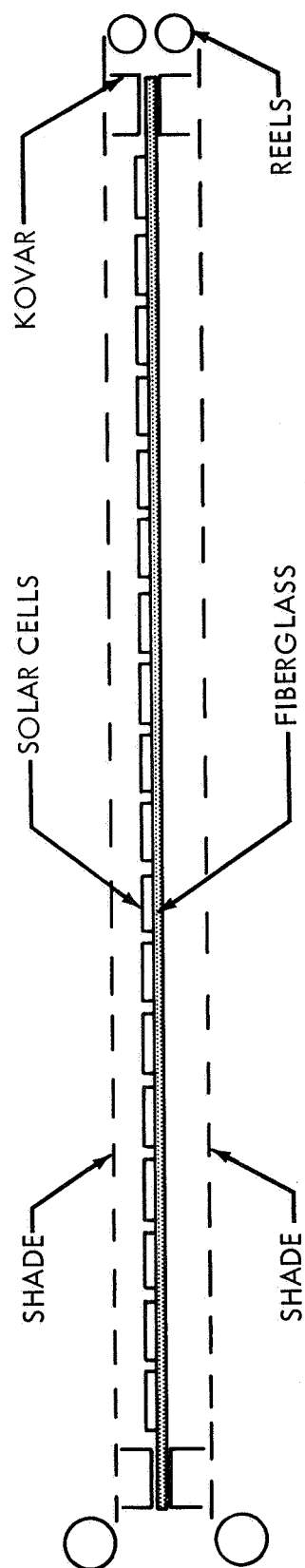
Figure 11: PRELIMINARY PANEL DESIGN

CONTRACT NO. NAS5-10445

NEW TECHNOLOGY

A thermal-diffusion bonding process has been developed for making metal bonds between the silver interconnector and the solar cell. The bonds have been tested, and the results of these tests are shown in the technical discussion.

In this new process, a silver interconnector is brought into contact with a solderless, silicon solar cell. A pressure of approximately 5600 pounds per square inch is applied to the joint, and the assembly is heated to 400°C in vacuum, then allowed to "soak" for 20 minutes. A properly made bond is a metal diffusion of silver into silver and is as strong and as electrically conducting as the silver itself. It has withstood 10 cycles from 20 to 500°C and should withstand temperatures up to the melting point of silver. This process, which eliminates the need for solder and fluxes, appears adaptable to mass production.

PROGRAM FOR NEXT REPORTING INTERVAL

The work that will be done for the next quarter is as follows:

1)   Continue interconnector bonding development;

2)   Test and select an adhesive for bonding the solar cells to the substrate;

3)   Finish the thermal analysis;

4)   Design the shade and accessory equipment.

The interconnector bonding development will undoubtedly continue until the last solar cell is bonded to the interconnector and placed on the panel. However, during the next quarter a statistical analysis will be made on 20 solar cells to determine if a significant change has occurred in solar cell performance during processing. The analysis will consist of two tests, the "F" test and the "t" test, and will be made at a 95% confidence level. The "F" test provides a means of determining whether there is a significant difference between the variances of two groups of data.

$$F = S_m^2 \; / \; S_n^2$$

where S_m^2 is the variance of Data Group 1 with m degrees of freedom, S_n^2 is the variance of Data Group 2 with n degrees of freedom and $S_m^2 > S_n^2$. Variance is a measure of dispersion of a frequency distribution.

Calculations and use of variation and standard deviation are found in texts. The "t" test is used to test for the significance of the difference between two means. With this test we can determine whether the difference between two means may be due to chance, and that the process has not necessarily made a change in the characteristics of the cells; or we can determine that the two averages do differ with any desired degree of certainty.

For paired variates with before-and-after data obtained on the same samples:

$$t = \frac{\overline{X}}{S\sqrt{n}}$$

where $\overline{X} = \Sigma_i \, (X_{B_i} \Sigma - X_{A_i})/n$

X_B = before data

X_A = after data

S = standard deviation of the difference data

n = number of data points

A modification to the equation for "t" must be made if the comparison is to be made between unpaired variates, i.e., not the same samples for both sets of data.

If both sets of data are of the same sample size, then

$$t = \frac{\left(\overline{X}_1 - \overline{X}_2\right)}{(S_1 + S_2) \, / \sqrt{n}}$$

where $\overline{X}_1 = \frac{\Sigma X_i}{n}$, $\overline{X}_2 = \frac{\Sigma X_j}{n}$ and S_1 and S_2 are the respective standard devia-tions of the sets of data.

Electrical parameters will be obtained from volt-ampere curves of the cell illuminated with a xenon light source at an intensity of 100 mw per sq cm as determined with Heliotek standard cell No. 130. The test cell mounting block will be maintained at $28 \pm 1°C$. The parameters to be statistically evaluated from the curve will be the short-circuit current, I_{sc}, open-circuit voltage, V_{oc}, and the current at 0.47 volt, $I_{0.47v}$, which is near the maximum-power point of the cells.

If a significant statistical change has occurred, then an engineering evaluation must be made to determine whether the change has significance affecting the practical operation of a solar array.

Adhesives have been obtained from the Sauereisen Cements Co. and from Aremco Products, Inc. These cements will be used to bond solar cells to strips of fiberglass cloth. The solar cell will be tested for adhesion both before and after thermal cycling from 20 to 450°C, and the chemical reaction between cemented parts will be observed for several weeks to ensure that the cements do not attack the solar cells or the fiberglass cloth.

The thermal analysis on the greenhouse effect will be completed as soon as additional information on the coated and uncoated H-film is obtained. This analysis will show the number of layers of H-film required to attain a steady-state temperature of 450°C and the time required to reach this temperature.

The electrical heating analysis will continue, and solar cells will be checked for degradation after being tested with 0.8 ampere forward current at 450°C. If there is no degradation, a load profile will be made to show the heat dissipated at 0.8 ampere from 20 to 450°C, and the time to heat the panel to 450°C will be calculated. The number of layers of aluminum foil versus power required will also be determined, and a recommendation on how to heat the panel will be made.

The shade, reels, and accessory equipment for drawing the shades across the panel will be designed after the thermal analysis is completed.

CONCLUSIONS AND RECOMMENDATIONS

From the work accomplished during the first quarter of the program, the following conclusions can be made:

1) Thermal-diffusion bonding can be used to attach interconnectors to solar cells;

2) In three out of four cases, thermal-diffusion bonding did not degrade the performance of the solar cells;

3) Joints formed by thermal-diffusion bonding have more than 500 grams shear strength;

4) The bonded joint is a well-diffused joint;

5) A solar cell and a bonded interconnector joint can withstand 10 cycles from 20 to 500°C without separation;

6) A 400-Hz motor will operate in vacuum.

Thermal-diffusion bonding appears to have many advantages beyond the high-temperature requirements of this contract. It eliminates the weight of solder, the contamination of fluxes, and the cleaning after joining, and allows the cells to experience high temperatures without interconnector joint failure. The process appears to be adaptable to mass production. It is not within the scope of this contract to fully investigate all the parameters of thermal-diffusion bonding to solar cells, but rather to develop the process to a point where it is suitable for fulfilling the contractual committments. The work required to fully develop the process appears to be a research program in itself.

PROGRAM SCHEDULE

The program schedule is shown in Figure 12. The darkened areas show the work completed. At this time, all work is proceeding on schedule.
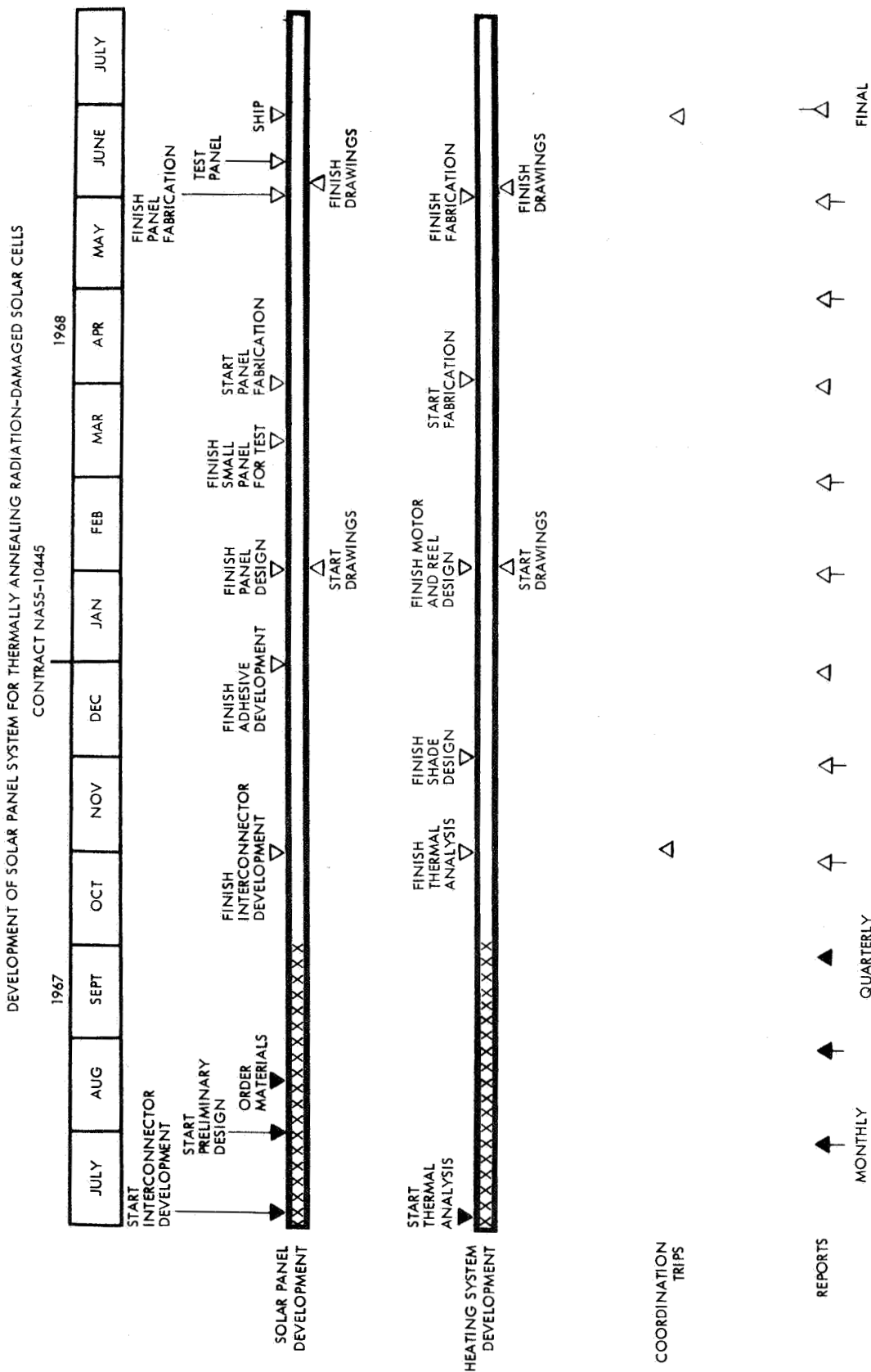
DEVELOPMENT OF SOLAR PANEL SYSTEM FOR THERMALLY ANNEALING RADIATION-DAMAGED SOLAR CELLS

CONTRACT NAS5-10445

	1967						1968					
JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY

SOLAR PANEL DEVELOPMENT

START INTERCONNECTOR DEVELOPMENT

START PRELIMINARY DESIGN

ORDER MATERIALS

FINISH INTERCONNECTOR DEVELOPMENT

FINISH ADHESIVE DEVELOPMENT

FINISH PANEL DESIGN

FINISH SMALL PANEL FOR TEST

START PANEL FABRICATION

FINISH PANEL FABRICATION

TEST PANEL

SHIP

START DRAWINGS

FINISH DRAWINGS

HEATING SYSTEM DEVELOPMENT

START THERMAL ANALYSIS

FINISH THERMAL ANALYSIS

FINISH SHADE DESIGN

FINISH MOTOR AND REEL DESIGN

START FABRICATION

FINISH FABRICATION

START DRAWINGS

FINISH DRAWINGS

COORDINATION TRIPS

REPORTS

MONTHLY

QUARTERLY

FINAL

Figure 12:   PROGRAM SCHEDULE

31

CONTRACT NO. NAS5-10445

BIBLIOGRAPHY

1. Springgate, F., "Development of Electrical Design Concepts for a Large Area Solar Array," IECEC, August 13, 1967, Miami Beach, Florida.

2. Fang, P. H., _Thermal Annealing of Radiation Damage in Solar Cells_, NASA/Goddard Document X-713-65-468, November 1965.

3. Garrett, B. R.; Blank, G. F.; and Ranadive, A. J., _Broad Applications of Diffusion Bonding_, NASA Contractor Report NASA CR-409, March 1966.

4. Fang, P. H., "Thermal Annealing of Radiation Damage in Solar Cells," _Astronautica Acta_, Vol. 13, pp. 147-157.